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# Investigation of Bistable Piezo-Composite Plates for Broadband Energy Harvesting

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In recent years there has been an increase in the use of wireless sensor networks and electronics requiring a portable energy source. As a result energy harvesters have emerged to convert ambient vibrations to electrical energy via mechanisms such as electrostatic generation, electromagnetic induction or the piezoelectric effect. Vibration based harvesting devices are often tuned to operate near resonance to maximize their power generation however, resonant devices are not easily scalable and their performance falls significantly away from these frequencies<sup>1</sup>. This renders such linear resonant systems unsuitable where vibrations exhibit multiple time-dependent frequencies. It was recently discovered<sup>2</sup> that a nonlinear  $[0_2/90_2]_T$  bistable composite plate with bonded piezoelectric layers is effective over a wider range of frequencies, exploiting the large amplitude oscillations between the two stable states.

This paper reports the static and dynamic behavior of a bistable composite plate excited by mechanical vibrations via experimental and modeling studies. The two stable states of a  $[0/90]_T$  composite plate with a piezoelectric layer attached to the top surface are shown in Fig. 1a. The device is mounted to a mechanical shaker from its center, Fig. 1b. To aid actuation and provide higher plate curvatures, thus increased electrical outputs, masses are attached to the plate corners in the form of steel bolts (~12 g each). The test area is lit to aid displacement capture via a Digital Image Correlation (DIC) system. This system captures high speed stereo images (5000 fps) and compares a speckled surface pattern to a reference image at each time interval. An accurate map of the displacements ( $\pm 0.1$  mm) is generated capturing the dynamic oscillations.

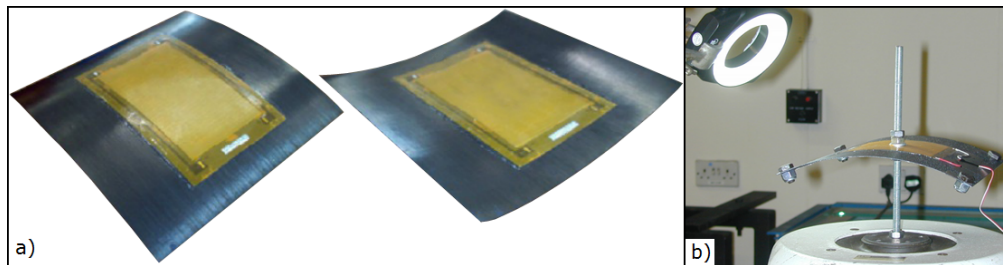


Figure 1. a) Stable states of a  $[0/90]_T$  piezoelectric plate, and b) experimental setup showing mechanical shaker attachment.

The differing modes of oscillation observed for a range of vibrational inputs are considered. Figure 2 shows phase plots of the corner displacement, selected from the DIC surface data, plotted against the driving velocity of the laminate center, a measure of the position within each cycle. Figure 2a shows repeatable snap-through between the two shapes seen in Fig. 1a (18Hz, 3.5mm peak-to-peak center displacement), exhibiting substantial changes in corner displacement. Figure 2b shows intermittent snap-through (20.8Hz, 9mm) where the large displacement change is only observed for every second cycle, reducing the total power output. Figure 2c shows a less uniform response (20.8Hz, 7mm) which further reduces power generation. The harvested power is therefore highly dependent on the vibrational input.

For the repeatable pattern of Fig. 2a, the associated voltage outputs are shown in Fig. 3. The peak-to-peak voltage change is similar for each actuation from shape 1 to shape 2 and the reverse. Taking a capacitance  $C$  for the piezoelectric layer of 800nF, measured experimentally, and a voltage change  $V$  of 42V (Fig. 3) the electrical energy associated with each actuation ( $\frac{1}{2}CV^2$ , twice per full oscillation) is 0.71mJ, giving a power of 25.4mW for a frequency of 18Hz. Applications for wireless sensor networking to date have focused on environmental monitoring where nodes tend to have low-power sleep states (10-300 $\mu$ W) with higher power requirements for transmitting and receiving data (500 $\mu$ W-60mW)<sup>3</sup>. The example power output of 25.4mW represents an arbitrarily chosen load resistance and device geometry for an off-resonance vibration input. However this value compares favorably with typical power requirements.

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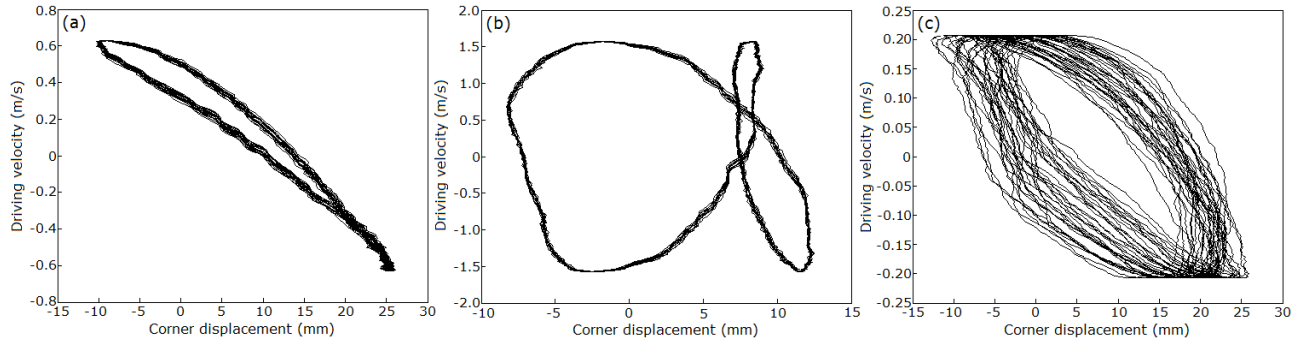


Figure 2. Phase plots showing a) repeatable snap-through (18Hz, 3.5mm peak-to-peak center displacement), b) intermittent snap-through (20.8Hz, 9mm), and c) a less uniform response (20.8Hz, 7mm).

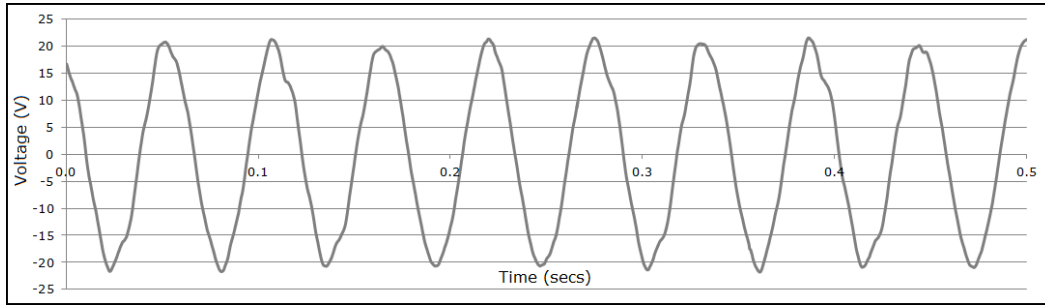


Figure 3. Voltage outputs for a repeatable actuation cycle (vibrations at 18Hz and 3.5mm peak-to-peak center displacement).

We develop a dynamics model for this system, extending the existing static model<sup>4</sup> and using the findings of the experimental studies presented here. Finite element analysis is used to understand the complex phenomena and includes the effects of geometric imperfections and manufacturing asymmetry. The initial curved plate shapes resulting from cooling from the elevated manufacturing temperatures, the dynamic response to mechanical vibrations, and the power outputs obtained experimentally are compared with finite element modeling results using ABAQUS. The composite plate is modeled using S4R doubly curved shell elements with 4 nodes per element and reduced integration, while the corner masses are solid C3D8R elements. The piezoelectric layer is modeled using C3D20RE solid elements with an additional electric potential degree of freedom. To model the electrodes covering the entire top and bottom piezoelectric surface (P2-type MFC) the surface nodes are tied to ensure a uniform potential. The potential on the bottom electrode is constrained to zero while the top surface is allowed to vary with the mechanical vibrations. This finite element model will provide natural frequencies associated with each stable device shape, full characterization of the varying modes of oscillation demonstrated experimentally, and power outputs for a broadband range of inputs.

The full paper will draw the three areas of experimental data, analytical modeling and finite element modeling together to form a comprehensive investigation of the piezoelectric bistable composite plates as a means of converting waste vibration energy into harvested electrical energy.

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